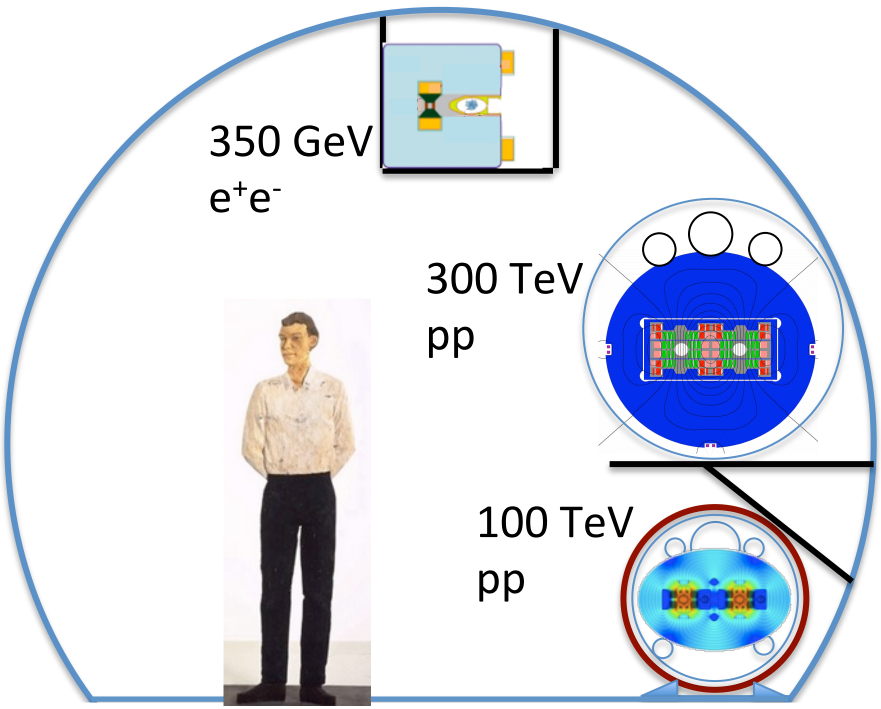
Large Circumference, NbTi Cable-in-Conduit: Industrialization for a 100 TeV Hadron Collider



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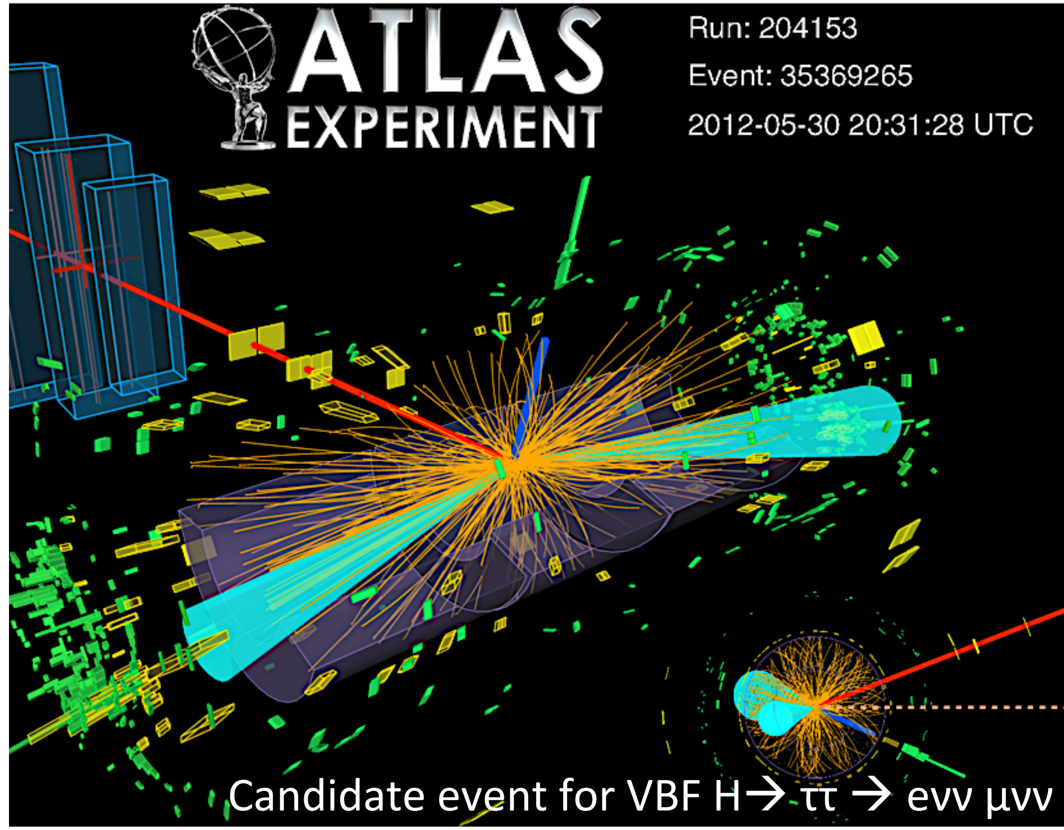
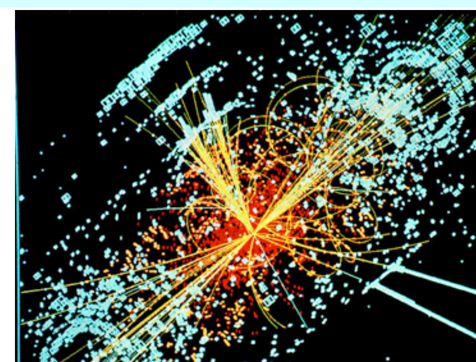
Texas A&M University

On July 4, 2012 CERN announced the discovery of the Higgs boson.
With its discovery, the Standard Model of fundamental gauge fields of nature was complete.
But…

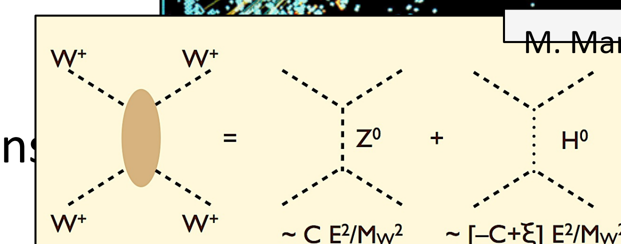


Candidate event for VBF H→ ττ → eνν μνν

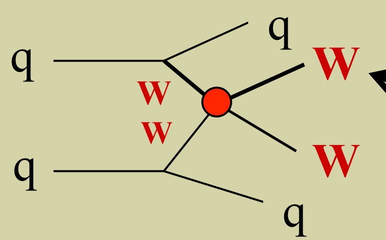
1. We cannot resolve the gauge field nature of the scalar sector of which the Higgs is the field carrier:
   - ➢ Is there one Higgs or are there are family of them?
   - ➢ How does the Higgs boson couple to the field carriers of the strong and electroweak interactions?



Problem: in hadron collisions the gluon collision that produces a Higgs is accompanied by multiple other collisions – too complex to fully resolve and interpret each event.

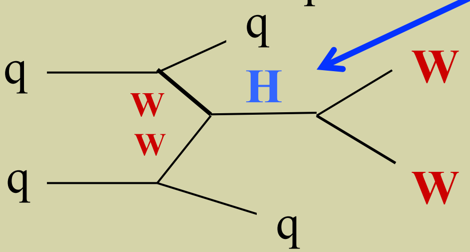


Q1: Does the new particle fix the SM "nonsense" at large m_{VV} ?



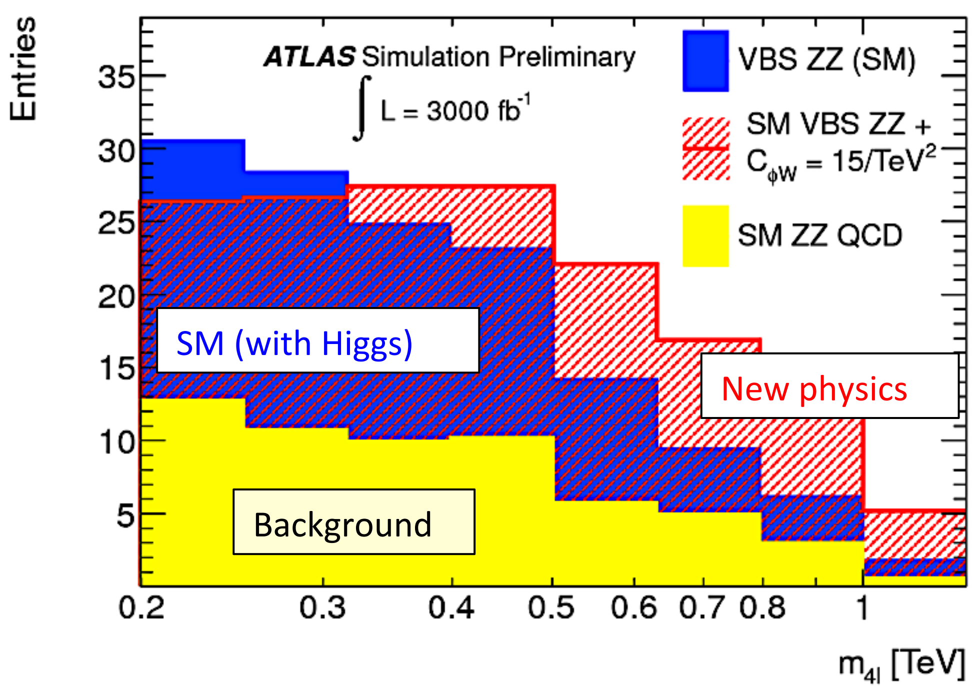
This process violates unitarity: $\sigma \sim E^2$ at $m_{WW} \sim$ TeV (divergent cross section → unphysical)

if this process does not exist



→ Important to verify that the new particle accomplishes this task → a crucial "closure test" of the SM

→ Need √s ~ 14 TeV and ~3000 fb^{-1}



If no new physics: good behaviour of SM cross section can be measured to 30% (10%) with 300 (3000) fb^{-1}

If new physics: sensitivity increases by ~ 2 (in terms of scale and coupling reach) between 300 and 3000 fb^{-1}

→ HL-LHC is crucial for a sensitive study of EWSB dynamics

CERN has launched a design study for a Future Circular Collider:
100 TeV Hadron Collider + e^+e^- Higgs Factory

The FCC Collaboration has made the physics case for a large circular collider as a basis for the next generation of HEP:

Example from Mustafayev @ MWCDMP2014:
SUSY spectrum to preserve naturalness… is above LHC reach, all within reach for √s = 100 TeV.

Summary of Natural spectrum

- For $m_h \sim 125$ GeV and $\Delta_{EW} < 30$:
  - $\mu \sim$ 100-300 GeV
  - stop_1 ~ 1-2 TeV, stop_2 = sbottom_1 ~ 2-4 TeV, highly mixed by large A_t
  - gluino ~ 1-5 TeV
  - 1st/2nd generation squarks ~ 1-10 TeV
  - sleptons ~ 1-30 TeV
- This can be realized in a simple extension of mSUGRA, NUHM2
  $$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu,\ m_A$$
- Here small $m_{H_u}^2 \simeq -M_Z^2$ and lighter stops are generated by RGE evolution, hence Radiatively-driven Natural SUSY (RNS)

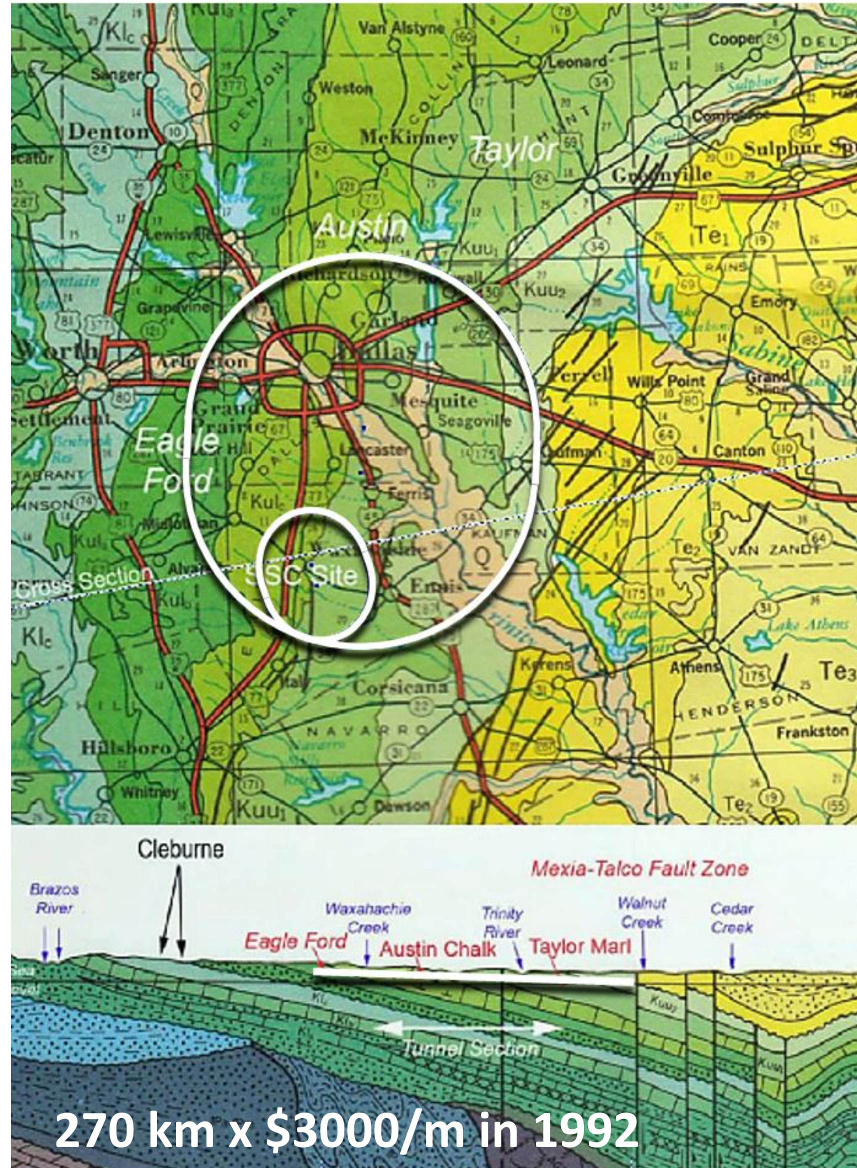
CERN's FCC design studies assume a tunnel circumference of 80-100 km.

- 80 km tunnel circumference is fine for a Higgs factory, and we have one we would like to offer you…
- 80-100 km circumference is a painful choice for a 100 TeV hadron collider because it pushes magnet technology to ~16 T, and has very high synchrotron radiation into the aperture.
- **Is that really the most cost-effective choice? Suppose one sought a larger circumference and lower dipole field for the ultimate hadron collider…**

Our motivation: create a workable path to restore leadership in high energy research to the US

- P5: *Without the capability to host a large project, the U.S. would lose its position as a global leader in this field, and the international relationships that have been so productive would be fundamentally altered.*
- We describe a design that minimizes the cost for a 100 TeV hadron collider;
- The minimization benefits uniquely from a US site;
- The magnet technology can be industrialized so that all industrial nations can make magnets as partners.

Tunnel cost depends strongly upon the rock in which you tunnel



There is already an 80 km circumference tunnel in Texas – the SSC tunnel was nearly completed.

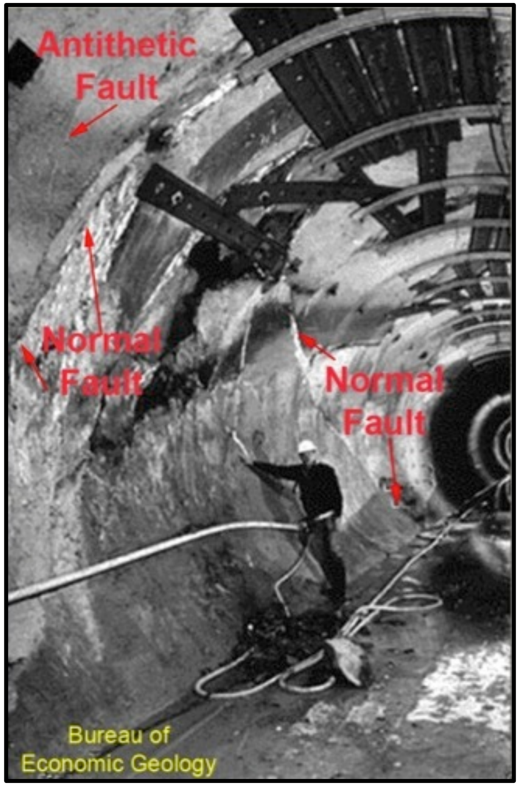
The tunnel is contained in the Austin Chalk and the Taylor Marl – two of the most favorable rock types.

Tunneling the SSC set world records for tunneling advance rate – 45 m/day. That record holds today!

A 270 km tunnel can be located at the same site, entirely within the Austin Chalk and Taylor Marl, tangent to the SSC tunnel as injector.

SSC tunnels are in Austin Chalk and Taylor Marl: Nature's perfect tunneling medium

Experimental hall was stable even without lining – homogeneous, minimum inclusions, self-arching



Even at an inactive fault, tunnel advance rate remained at the record 45 m/day

Compare 5 sites for a 270 km tunnel

location	main rock type	cost comparables	length (km)	mean diam. (m)	cost ($M)	cost/m scaled for 4 m diam. scaled by CCI	cost of 270 km tunnel today ($B)
Geneva (CERN)	molasse /limestone	LEP (1980) [1]	27.0	3.8	338	38,863	**10.47**
	dolomite	Gothard(2013) [2]	57.0	8.0	13,000	57,000	**15.39**
Dallas site	chalk/marl	SSC (1992) [3]	39.0	4.2	130	6,080	**1.65**
Fermilab site	dolomite	TARP (2006) [4]	173.0	8.2	3,600	14,748	**3.97**
Indianapolis	dolomite	Fall Creek (2011) [5]	36.4	5.3	389	8,504	**2.29**
San Antonio	marl	San Antonio (2011) [6]	4.9	7.3	84.4	9,934	**2.68**

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1 H. Schopper, 'LEP - the Large Electron Collider project', http://lss.fnal.gov/conf/C8405141/p.43.pdf

2 F. Amberg, 'Gotthard Basetunnel: Aspects of Long Tunnels', FCC Kickoff Meeting, Geneva, Feb. 12-14, 2014, http://indico.cern.ch/event/282344/session/6/contribution/23

3 P. Nelson, 'Tunneling and Construction at the Dallas - Ft. Worth SSC Site', SSC-N-625 (1989).
M. Werner *et al.*, 'Bedrock Geology of the SSC Site', SSC-SR-1124 (1990).
T.F. Martin, SSC Contract Bid Data, private communication.

4 Metropolitan Water Reclamation District of Greater Chicago, Tunnel and Reservoir Plan, http://www.mwrd.org/irj/portal/anonymous/tarp

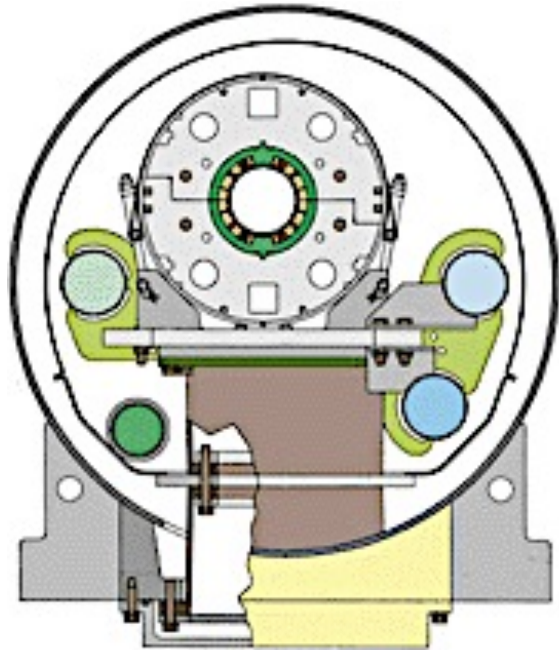
5 Fall Creek/White River Deep Storage Tunnel, http://www.citizensenergygroup.com/pdf/projects/FallCreekWhiteRiverTunnel.pdf.

6 San Antonio River Authority, https://www.sara-tx.org/public_services/past_projects.php

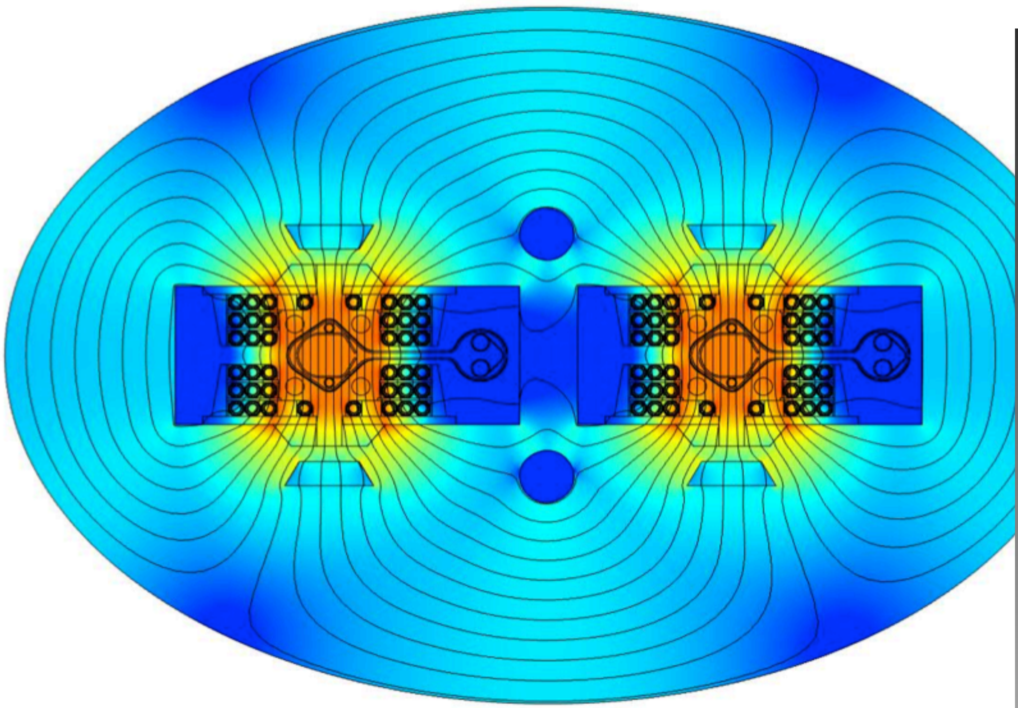
We have explored what the FCC collider complex would be like in a 270 km tunnel

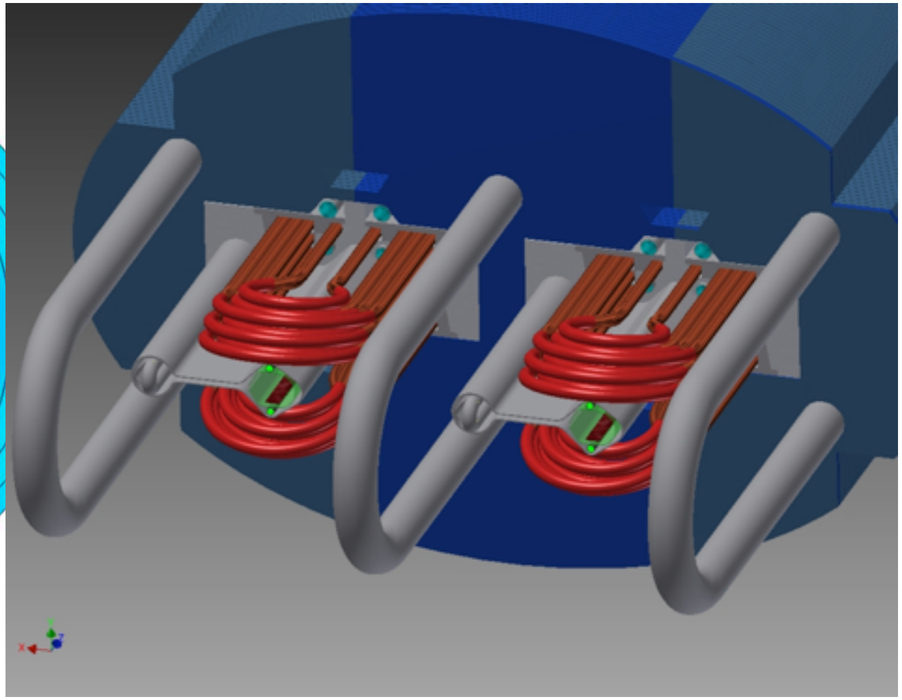
- **100 TeV hadron collider requires 4.5 T magnets**
  - RHIC dipole (3.5 T @ 4.5 K) is simple, single-shell dipole,
  - mfg. in industry, simple structure, modest forces
  - But each dipole cost 30 times more than the superconductor inside it!

- **LHC dipoles cost ~3 times more than their superconductor**
  - We need a dipole with inexpensive superconductor, simple fabrication.



We have devised a way to combine the simplicity of the low-field superferric SSC dipole with a cable-in-conduit conductor:





60 cm

- 4.5 Tesla dipole field
- C-dipole: synchrotron radiation passes into a second chamber where it is absorbed at 150 K.
- Refrigeration is 100x more efficient, so heat load not a limit.
- Clearing electrode suppresses electron cloud; 25 ns bunch spacing feasible.
- Superconducting winding has 20 turns total, wound from 2 pieces of round cable-in-conduit.

The 4.5 T NbTi dipole is key to manufacturability and cost

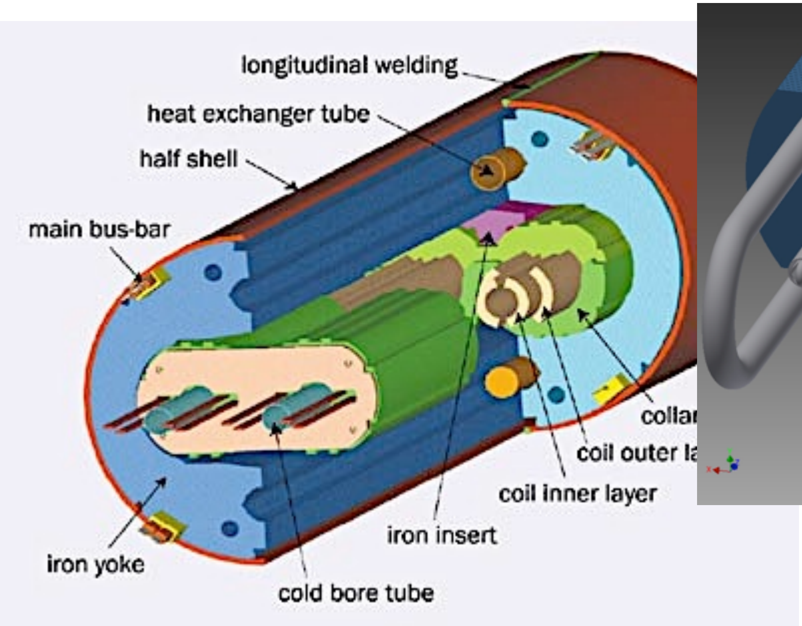
- Each dipole winding contains a total of 20 turns of cable.
- Quench protection is provided by driving current pulse in cable sheath – quenches all turns without voltage spike.
- Total cross-section of superconducting strand in one dipole is 8 cm^2 NbTi.
- Compare to 39 cm^2 NbTi for LHC,

  105 cm^2 of Nb_3Sn and 32 cm^2 of NbTi for 16 T dipole.
- Total cost of superconductor for 16 T ~$10.2 billion.
- Total cost of superconductor for 4.5 T ~$720 million.
- The challenge: reduce $\dfrac{\text{magnet cost}}{\text{conductor cost}} \Rightarrow 2:1$

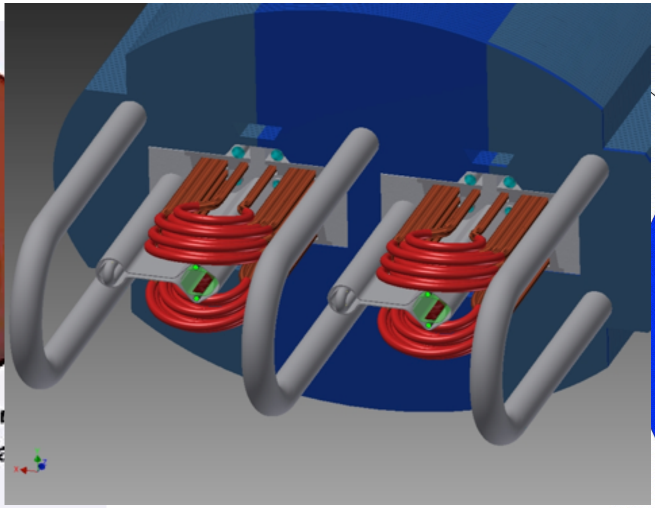
Everything that is tricky (cryogenics, quench protection) is contained within the cable. The dipole structure is then simple and passive.

The superferric magnets can be manufactured in any medium-scale metals industry if we provide proper tooling, training, QC. That is the key to obtaining partner contributions from ~50 nations for a New World Laboratory.

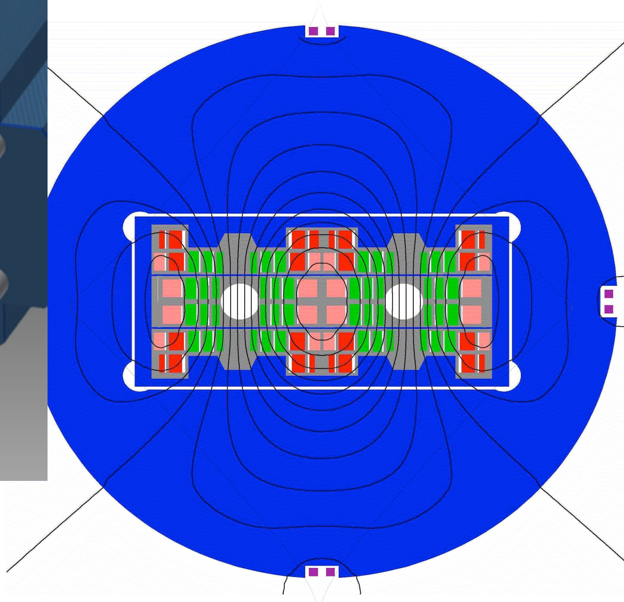
LHC NbTi



superferric NbTi

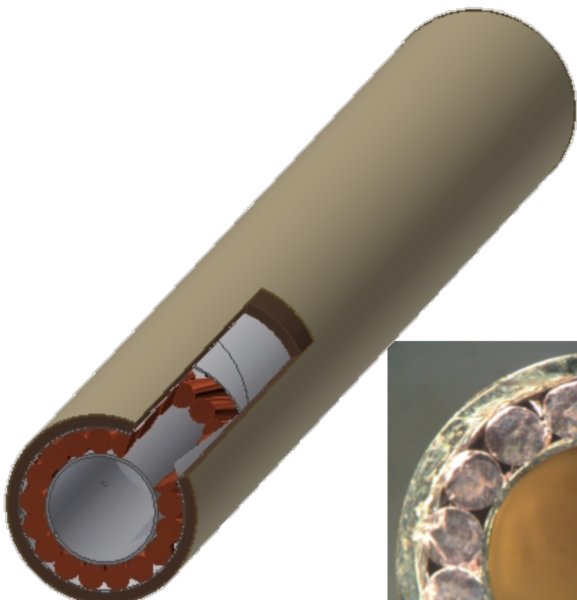


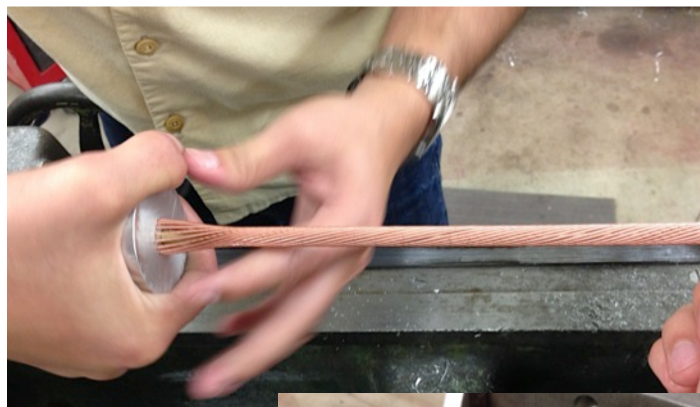
16 T Nb_3Sn/NbTi

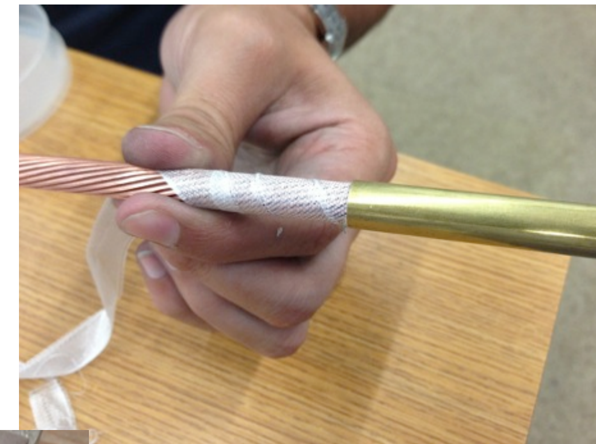


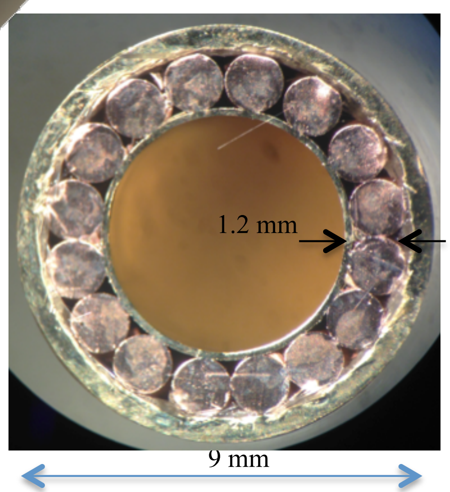
NbTi cable-in conduit

- Improve upon the CIC conductor developed by Dubna for FAIR:





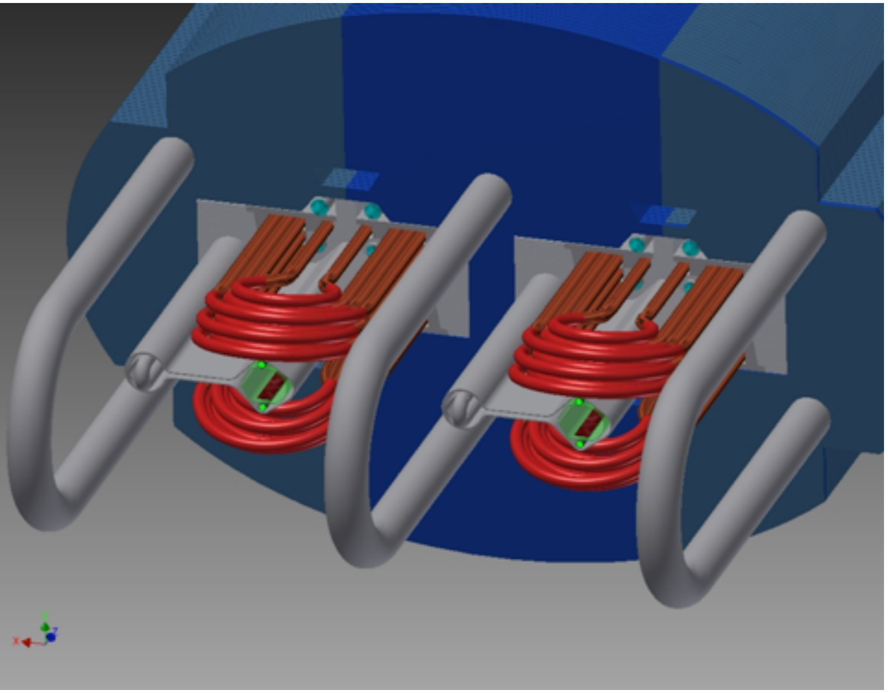


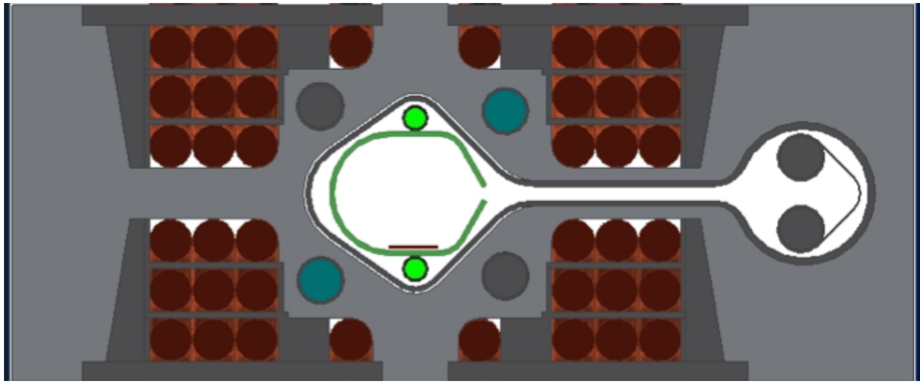


Motor and generator industries routinely manufacture large shaped windings like those of the CIC C-dipole.

They fabricate each winding in a single-fixture sequence: wind onto peg-pattern forms, bend ends of each layer using hinged platens.

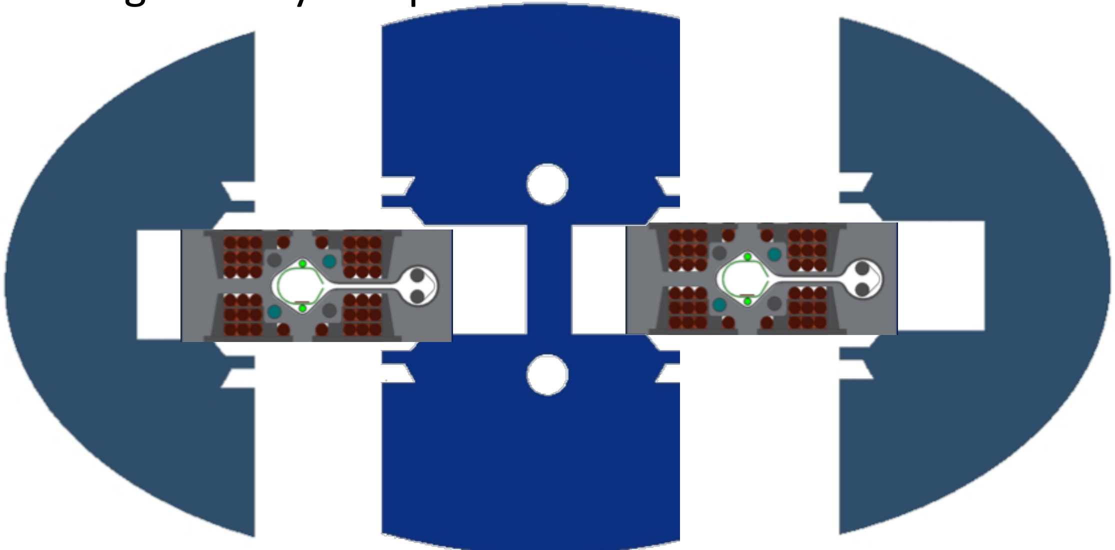
Manufacture of the dipole





2. Insert half-windings into one-piece lamination stack, insert wedges, compress/weld to preload and seal.

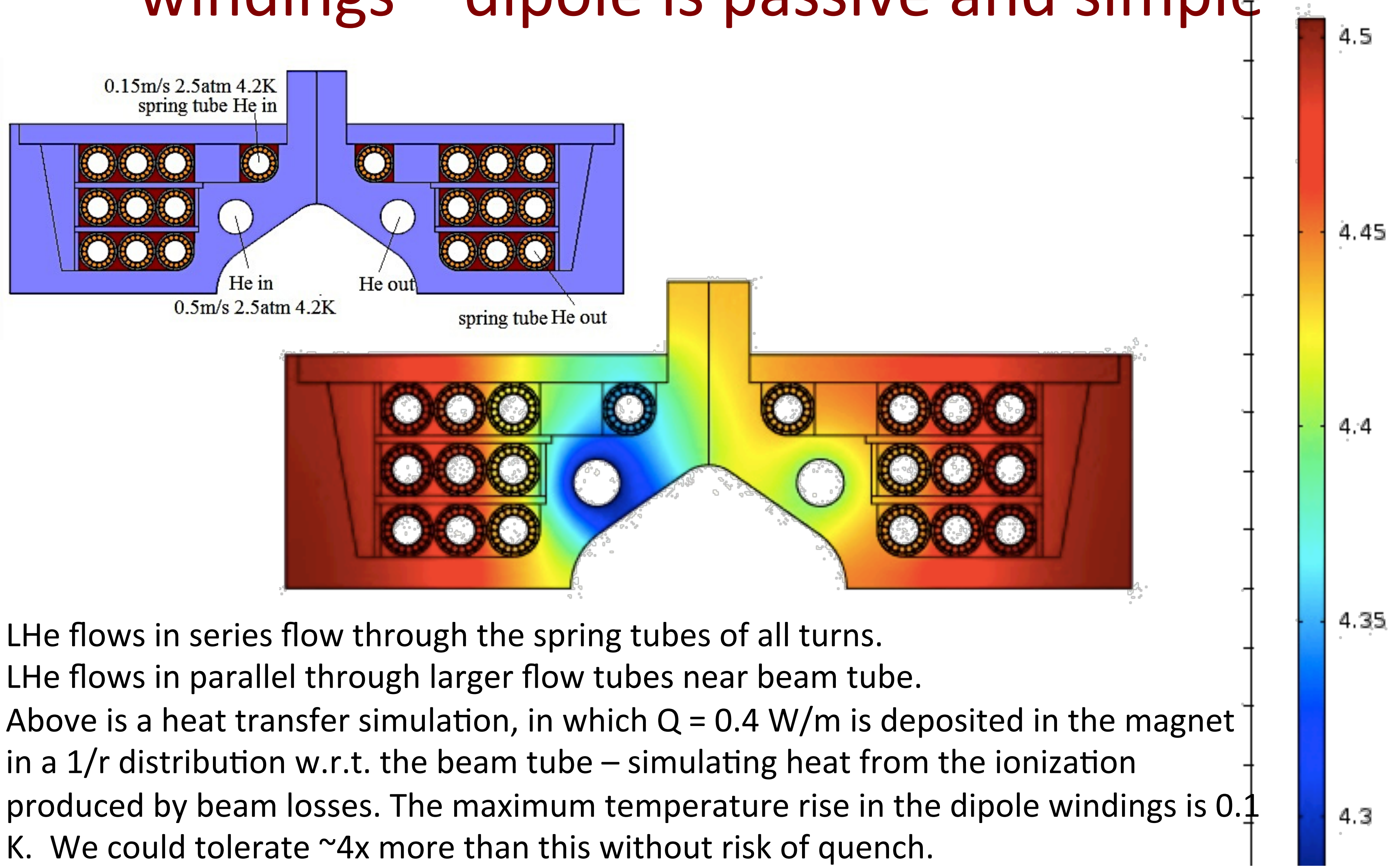
3. Vacuum-impregnate windings to lock coil geometry and preload.



1. Wind racetrack pancake windings for top/bottom halves - bend ends 90°.

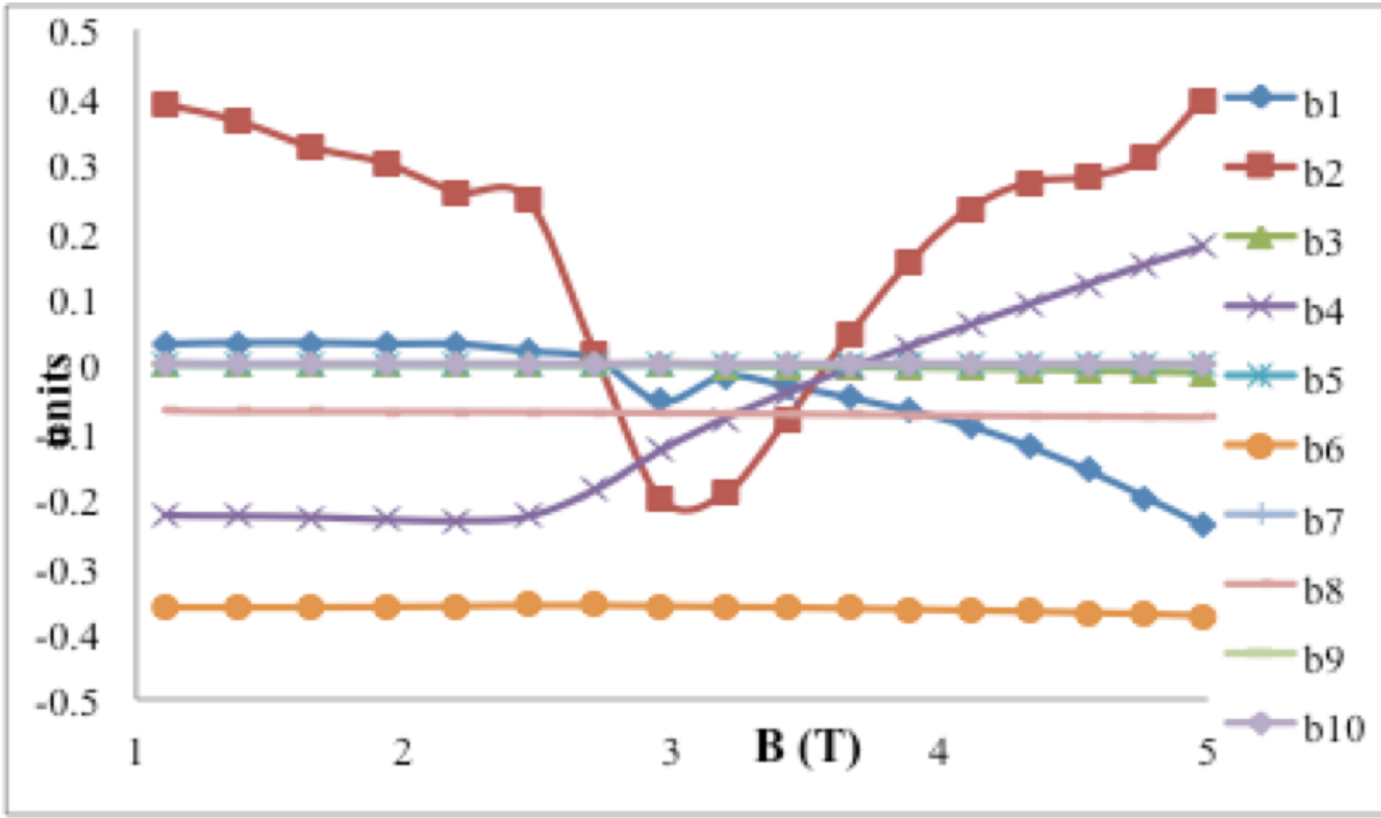
4. Install winding assemblies into flux return assemblies, compress and weld.

All cryogenics are integrated with the actual windings – dipole is passive and simple



LHe flows in series flow through the spring tubes of all turns.
LHe flows in parallel through larger flow tubes near beam tube.
Above is a heat transfer simulation, in which Q = 0.4 W/m is deposited in the magnet in a 1/r distribution w.r.t. the beam tube – simulating heat from the ionization produced by beam losses. The maximum temperature rise in the dipole windings is 0.1 K. We could tolerate ~4x more than this without risk of quench.
The dipoles are >10x more robust against beam-induced heat loads than LHC dipoles.

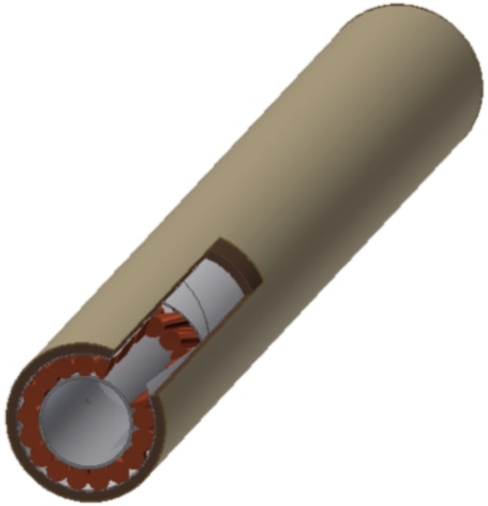
Multipoles are readily controlled to yield excellent dynamic aperture

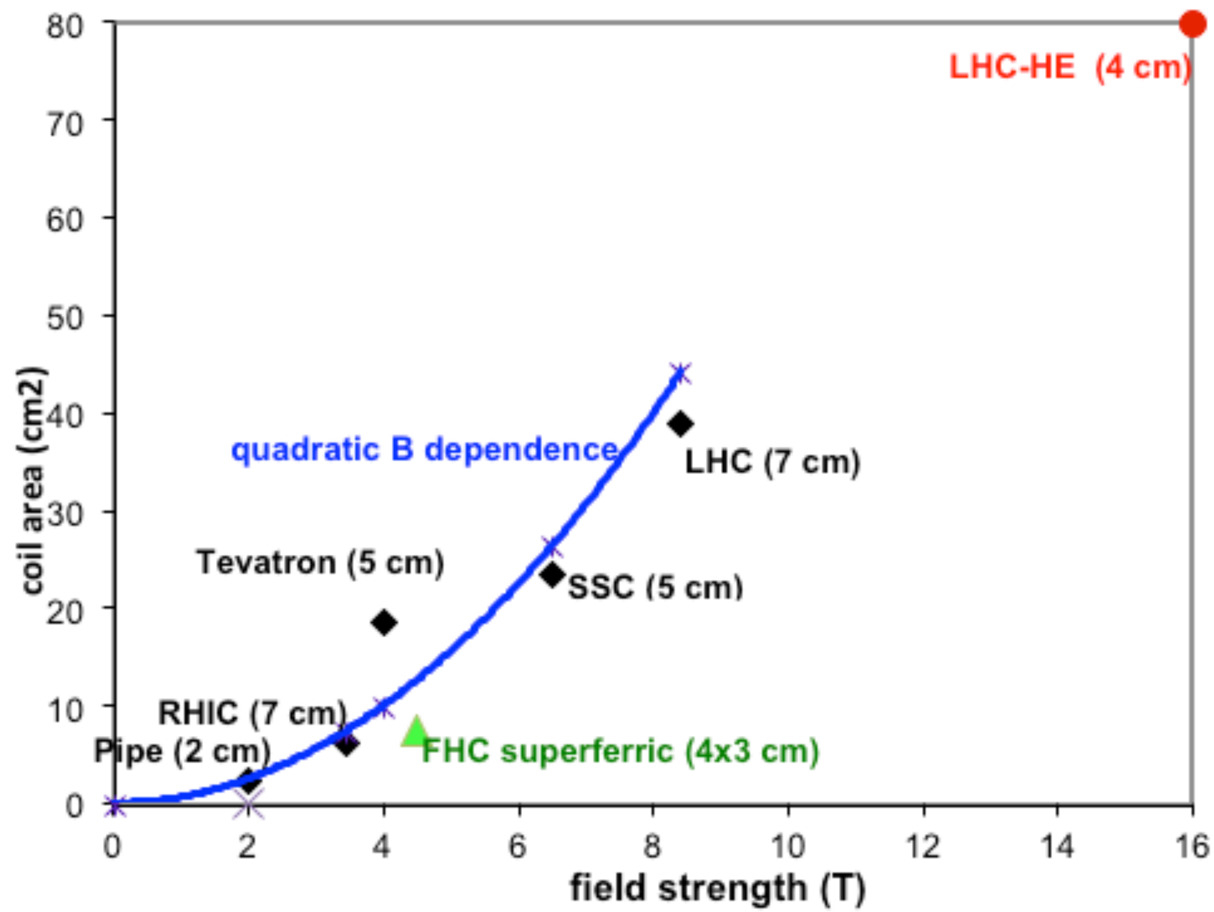


Compatible with stable high-luminosity collisions.

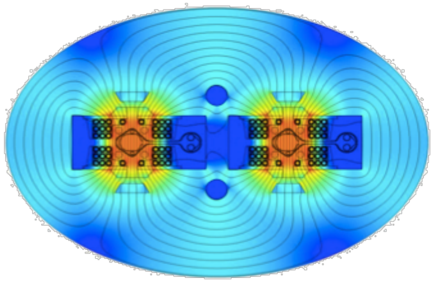
Momentum acceptance $\sigma_p/p > 5\text{x}10^{-4}$ sufficient for momentum stacking

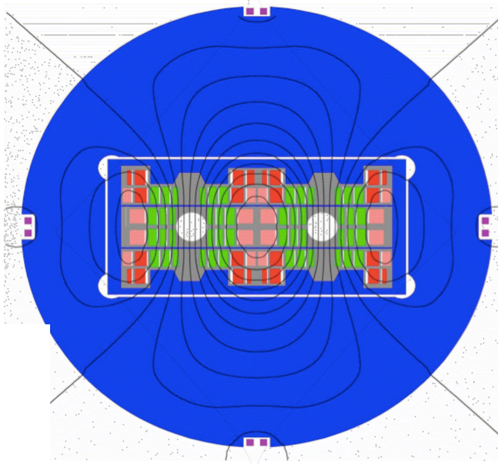
Superconductor cross-section vs. field for example collider dipole designs





Compare the costs for two dominant cost elements of the hadron collider: tunnel and superconducting wire





	RHIC	LHC	100 TeV 270 km	100 TeV 100 km
Operating field	3.4 T	8 T	4.5 T	16 T
# Bores	1	2	2	2
# turns per bore	32	74	20	
Length	9.4 m	14.3 m	20	20
Superconducting wire/bore: NbTi	48 kg	435 kg	120 kg	780 kg
Nb_3Sn				2,950 kg
Manufactured magnet cost	$105,000	$565,000		
Cost of superconductor	$4,800	$87,000	$210,000	$6,766,000
Magnet cost/m/bore/T	$3,265	$2,470		
Superconductor cost/T/m/bore	$150	$380	$1,164	$10,572
Superconductor cost for collider			$2,439 million	$22,828 million
Tunnel cost/m: CERN site				$38,863
: Dallas site			$6,080	
Tunnel cost:			$1,650 million	$3,863 million

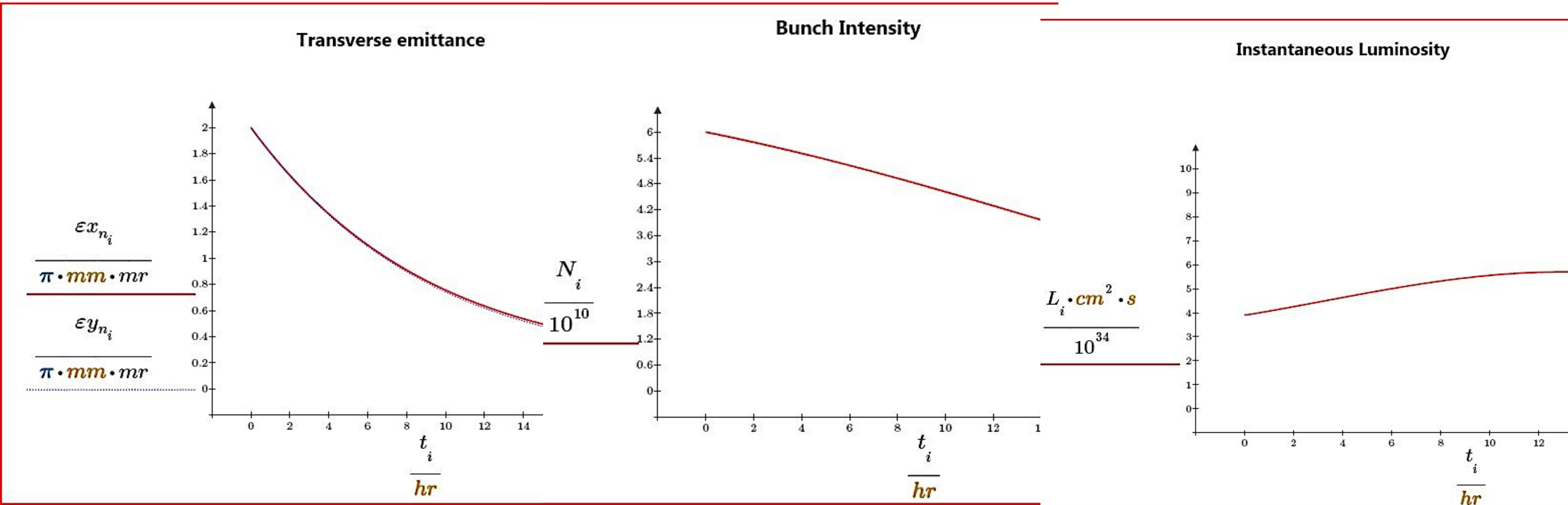
Challenge: simplify manufacture so that magnet cost ~2 s.c. cost

Parameters of the lepton and hadron colliders for medium and large circumference

	hadron collider			
Circumference	100	270		km
Collision energy	100	100	300	TeV
Dipole field	16	4.5	14.5	Tesla
Luminosity/I.P.	5	5	10	10^{34} $cm^{-2}s^{-1}$
β*	110	50	100, 10	cm
Total synch. power	4.2	1.0	34	MW
Critical energy	4.0	1.0	28	keV
Synch power/meter/bore	26	2	80	W/m
Emittance damping time	0.5	19	.66	hr
Luminosity lifetime	18	20	3.7	hr
Energy loss/turn	4.3	1.3	114	MeV
RF accel. voltage:	100	50	250	MV
Acceleration time	.20	.40	.25	hr
Bunch spacing	25	25	25	ns
Beam-beam tune shift	.01	.01	.01	
# IPs	2+2	2+2	2+2	
# particles per beam	100	220	86	10^{13}
Injection energy	>3	15	50	TeV
Superconducting temp.	4.5	8	4.5	K

100 TeV: Synchrotron damping dominates dynamics for luminosity, stacking

- The synchrotron damping time is ~4 h.
- Transverse emittance damps, luminosity is a balance between shrinking emittance and depletion of protons by collisions.
- Longitudinal emittance would damp, but we heat it using rf noise to prevent instabilities.



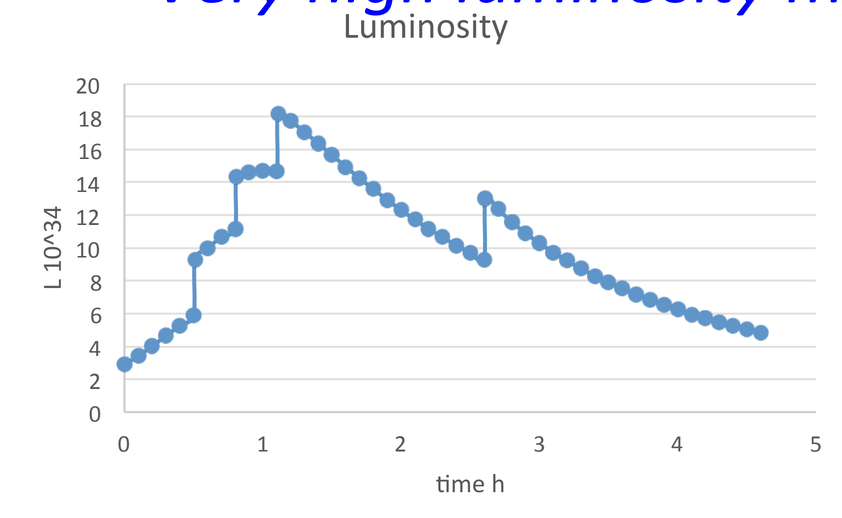
Bottom-up stacking to deliver maximum luminosity indefinitely

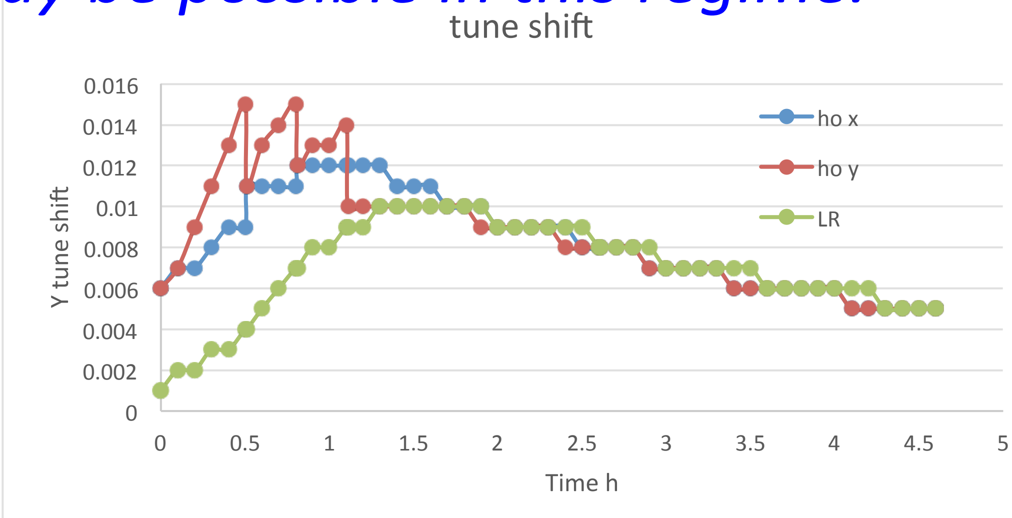
- When luminosity would begin to decrease due to proton depletion, turn off rf heating, decelerate to 15 TeV, scrape tails, and momentum-stack a fresh fill of protons along with the ones in the store.
- The momentum acceptance of the superferric dipole is sufficient to perform momentum stacking at 15 TeV injection energy – this is benefit of high-energy injector in SSC tunnel.
- RF voltage ~50 MV is required to provide sufficient bucket to capture and accelerate, and to replace synch rad at full energy.
- Re-accelerate and resume collisions.

This bottom-up stacking can be used to maintain maximum luminosity indefinitely. Down-time of each cycle ~40 min every ~4 h

300 TeV: Synchrotron damping ➔ flat beams

- Synchrotron damping time ~30 m.
- Synchrotron damping dominates the evolution of tune shift and luminosity.
- Beam begins x/y symmetric, and damps in y within ~30 min – y tune shift increases, luminosity increases
- Program β_y to maintain ~constant ξ_y ~ .01
- *Very high luminosity may be possible in this regime.*





Benefits of a large-circumference hadron collider for a Hadron Collider that can actually be built…

- pp @ 100 TeV: **industrial magnet technology**

  1/3 synch rad power

  injector in separate tunnel

  $B_{col}/B_{inj} = 0.3$ ➔ no field issues at injection, stacking OK

  Luminosity > 5×10^{34} $cm^{-2}s^{-1}$ indefinitely

- pp @ 300 TeV: **25 years to develop 16 T magnets**

  $B_{col}/B_{inj} = 0.3$ ➔ use 100 TeV collider as injector

  Luminosity >10^{35} $cm^{-2}s^{-1}$ indefinitely

Summary

- **We have identified a candidate site that could accommodate a 270 km tunnel for a 100 TeV hadron collider (using 4.5 T dipoles).**
- **We have developed a design for a 4.5 T superferric dipole that is simple/low-cost to build, operates at 4.5 K.**
- **Operation of a 100 TeV hadron collider is dominated by the refrigeration of heat from synchrotron light. We provide a separate channel for synchotron light, intercept it at high reservoir temp, so its heat does not dominate operating cost.**
- **Synchrotron radiation damps the beam in ~4 hours. We can maintain maximum luminosity indefinitely using a top-up scenario.**
- **The tunnel could accommodate a future 300 TeV upgrade.**
- **The magnets are simple:**
  - **Goal is magnet cost <4x superconductor cost.**
  - **Any industrialized nation could manufacture these magnets.**

How to build the collider in a world of finite $

- Ask Texas to build the 270 km tunnel as a State contribution.
  - ~$1 billion
- Form scientific partnership among member nations to build the lab and operate its scientific program.
  - Each country funds its own industries to build a share of the technical components for the collider.
    - ~$10-100 million, depending upon country – total ~$4 billion
    - Member nations fund ½ of operating budget.
- Ask US for major funding for conventional facilities, equipment.
  - US role is host country. This is a world laboratory, not a DOE laboratory. ~$2 billion capital, + ½ of operating budget.
- What is best way to coordinate design/build/funding of detectors?

P5: The U.S. could move boldly toward development of transformational accelerator R&D. There are profound questions to answer in particle physics, and recent discoveries reconfirm the value of continued investments. Going much further, however, requires changing the capability-cost curve of accelerators, which can only happen with an aggressive, sustained, and imaginative R&D program. A primary goal, therefore, is the ability to build the future-generation accelerators at dramatically lower cost.

Acqua alla funi…

P5 reported its findings next week.
It has recommended an ordering of priorities among the present research themes (LHC upgrade, neutrino experiments, dark matter searches) to cope with ever-shrinking US support for HEP.

	HEP	Amount in FY14$	% decrease with inflation since FY 96	% of Office of Science[1]	Office of Science total[1]
1996	$667 M	$1,045 M[2]		26.8%	$2,485.2 M[1]
2013	$776.5 M	$788.2 M[2]	-21.6%	15.5%	$5,001.2 M
2014	$796.5 M	$796.5 M	-23.8%	15.7%	$5,066.4 M
2015[4]	$744 M	$733 M[3]	-29.9%	14.6%	$5,111.2 M

In 1995 the top quark was discovered at Fermilab. ***That was the last major HEP discovery in the US.*** There is no prospect for another, unless dark matter or a sterile neutrino were discovered here.

Without discoveries – or the prospect of discoveries – in the US it is reasonable to expect that the US support of HEP will continue to decline.

Reversing that trend requires innovation: a new lab with credible potential for new discoveries; technology to make it affordable and to share the cost and the research leadership on a global scale; potential for a future upgrade to a further generation.